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Deep-Sea Misconceptions Cause Underestimation of Seabed-Mining Impacts

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Scientific misconceptions are likely leading to miscalculations of the environmental impacts of deep-seabed mining. These result from underestimating mining footprints relative to habitats targeted and poor understanding of the sensitivity, biodiversity, and dynamics of deep-sea ecosystems. Addressing these misconceptions and knowledge gaps is needed for effective management of deep-seabed mining.

Deep-Sea Minerals and Mining Regulation

The deep sea, that is, ocean depths below 200 m, constitutes more than 90% of the biosphere, harbors the most remote and extreme ecosystems on the planet, and supports biodiversity and ecosystem services of global importance. Deep-sea minerals of commercial interest include: (i) potato-sized polymetallic nodules that precipitate on sharks teeth and other hard particles on some abyssal plains; (ii) polymetallic (massive) sulfides deposited at hydrothermal vents along seafloor spreading centers; and (iii) cobalt-rich (ferromanganese) crusts precipitating on rock surfaces on some seamounts and ridges [1]. The International Seabed Authority (ISA) regulates seabed mining in areas beyond national jurisdiction, with a responsibility to protect the marine environment from serious harm (https://www.isa.org.jm/). The ISA has issued 30 contracts covering ~1.5 million km^2 for lower-impact mining exploration, which includes: resource assessment, environmental baseline studies, and test mining. The ISA is currently drafting exploitation regulations for potentially high-impact, full-scale mining, with the regulations to include environmental impact assessment, monitoring, and habitat protection. The ISA's mandate pertains to international waters; however, its exploitation regulations will also be relevant within 'exclusive economic zones.' The United Nations Convention on the Law of the Sea (Part XII, Article 208), specifies that environmental protections for seabed mining within national jurisdictions should be 'no less effective' than those developed by the ISA.

Polymetallic nodules, massive sulfides, and cobalt-rich crusts all provide critical habitat for deep-sea biota. Polymetallic nodules in the Clarion Clipperton Zone (CCZ), an area in the equatorial Pacific Ocean with the richest nodule resources, harbor diverse megafauna (e.g., ~100 species within a 30 × 30 km area) [2] and microbes not found in surrounding waters or sediments [3]. The biotic communities of nodules and sediments vary with nodule abundance [2] as well as along and across the CCZ [4]. Polymetallic sulfides at active hydrothermal vents provide habitat for novel faunal assemblages that have altered our views of the primary energy sources and origins of life, and exhibit substantial local and regional variation in structure and connectivity [5]. Polymetallic sulfide mining is expected to target 'extinct' vents due to the extremely corrosive nature of hot venting fluids, but active vents are not yet protected and extinct vents also have characteristic, albeit poorly studied, biotas [6]. Ferromanganese-encrusted seamounts support productive hotspots of biodiversity that vary within and among seamount chains [7]. Where mining removes or buries any of these three mineral habitats, the associated fauna will be damaged or destroyed.

To manage deep-seabed mining effectively, regulators, such as the ISA (with 167 member states and the EU) and additional stakeholders (e.g., civil society, industry, scientists, and other concerned parties), should utilize the best scientific predictions of mining impacts. Here, we address several misconceptions in the recent peer-reviewed literature concerning deep-sea ecosystems and the potential impacts of seabed mining. We also highlight knowledge gaps and uncertainties in predicting the spatiotemporal scales of mining disturbance and recovery, underscoring the importance of a precautionary approach, for example, limiting full-scale mining operations until impacts are well characterized.

Some Misconceptions

(i) The area disturbed by mining will be very small compared with the scales of deep-sea habitats (e.g., [8,9]). Thus, we can afford to lose the 'miniscule proportion' [8] of the vast seabed that will be affected by mining.

Seafloor mining targets specific deep-sea habitats with characteristic biotas that vary on scales of tens of meters and greater. As a consequence, the scales of impact may not be small when considering the distribution of the targeted habitats.

For example, for environmental management purposes, the CCZ has been divided into nine ecological subregions expected to have different seafloor communities [10,11] (Figure 1A), with substantial proportions of three of these subregions targeted for mining because they contain high nodule abundance (Figure 1A). Mining will permanently remove the habitat

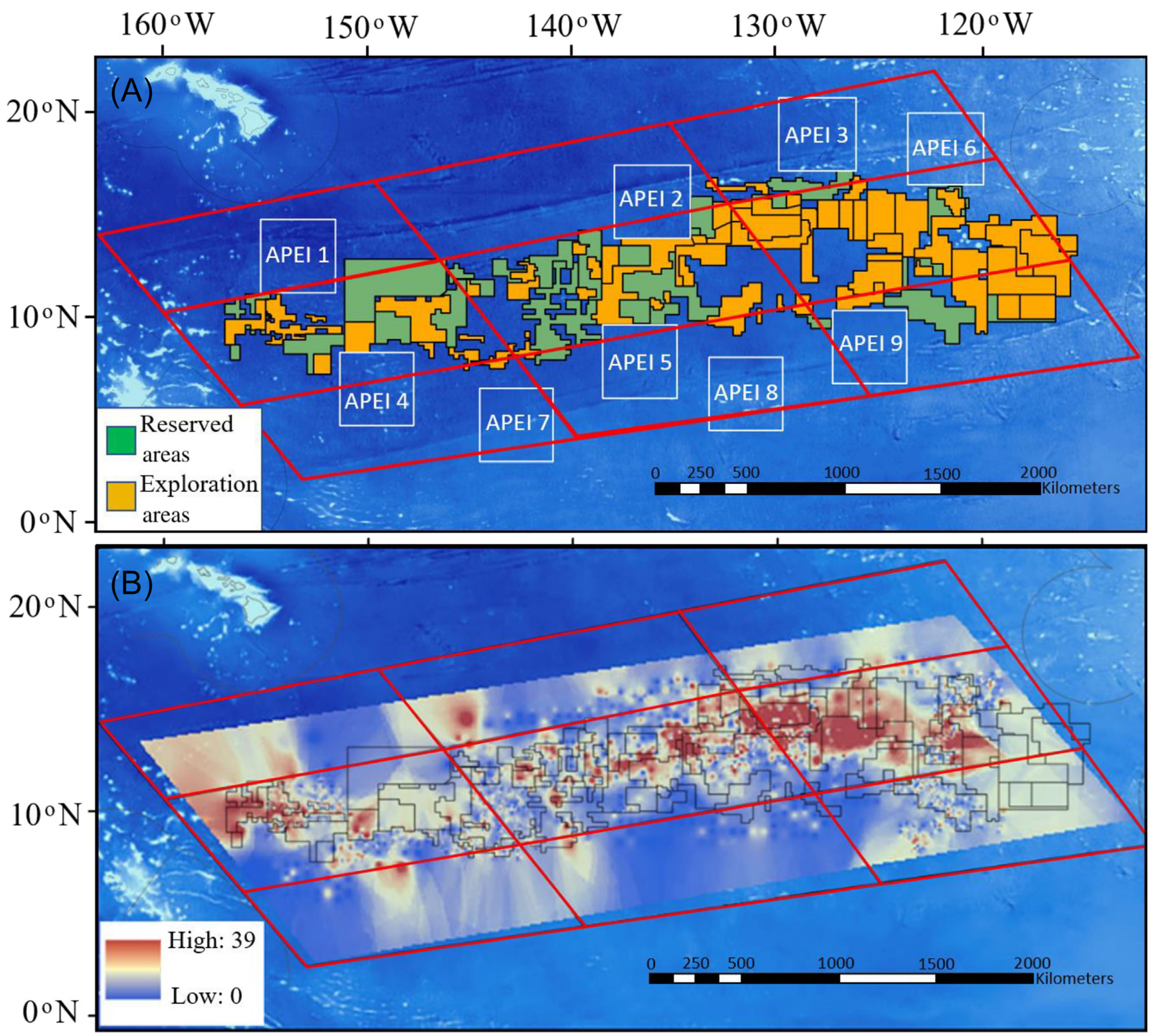

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Figure 1. Areas Targeted for Mining, Ecological Subregions for Management, and Nodule-Rich Areas in the Clarion Clipperton Zone (CCZ). (A) Region targeted for nodule mining in the abyssal Pacific CCZ, showing current mining exploration contract areas (orange blocks), areas reserved for mining but not yet allocated (green blocks), the nine ecological subregions expected to harbor different ecological communities (outlined in red), and areas of particular environmental interest (APEIs) (white boxes) protected from mining to safeguard biodiversity across the nine subregions. (B) Estimated polymetallic-nodule abundance at a 10 km grid size (inner parallelogram) projected onto the nine subregions. Continuous color scale in parallelogram: dark red = high nodule abundance (up to 39 kg m^{-2}); cream = moderate nodule abundance (~5 kg m^{-2}); blue = no nodules. Nodule exploration claims are concentrated in the three central subregions along the east–west axis of the CCZ where the largest nodule-rich areas occur. Nodule data from Wedding *et al.* [11].

for the nodule-dependent fauna in these subregions because nodules require 10^5–10^6 years to form [1,10]. This lack of recovery, combined with destruction of a high percentage of the nodule habitat within these ecological subregions and the entire CCZ (Box 1), could create real extinction risks for nodule-obligate biota.

By contrast, areas targeted for cobalt-rich crust mining are relatively small (~10–100 km^2 [1]), especially compared with nodule-mining footprints; but these crusts occur on seamounts, which often support assemblages of long-lived corals and sponges that create habitat for many other species [7]. Seamounts are globally abundant, yet their ecological significance, heterogeneity, the fragility of their fauna, and poor knowledge of their connectivity and biodiversity has resulted in the Food and Agriculture Organization (FAO) considering seamounts to be examples of vulnerable marine ecosystems (VMEs) subject to special protection from fishing activities (e.g., [7]).

Open-cut mines for polymetallic sulfides would likely have the smallest direct footprint (<10 km^2 per mine), although plume and associated ecotoxicological impacts could spread substantially further, for example, 10–100 km in pelagic ecosystems. These deposits form at seafloor hot springs known for specially adapted organisms that rely on inorganic chemicals, rather than sunlight, for their energy. The estimated global area of active hydrothermal vents is <50 km^2, making them an extremely rare habitat [5]. The small scales and remarkable biodiversity of hydrothermal-vent communities has led to their classification as VMEs by the FAO, and several vent fields are classified as ecologically or biologically significant areas (EBSAs) through the Convention on Biological Diversity [5]. Extinct sulfide deposits are also small in area, and so little is known about their biota [6] that it is premature to conclude that the loss of habitat and biodiversity from mining extinct deposits would be 'miniscule'.

(ii) Polymetallic sulfide communities will recover rapidly from mining (e.g., [9]).

Some active-vent communities on the East Pacific Rise, and on the Juan de Fuca Ridge (in the northeast Pacific), recover rapidly from frequent volcanic eruptions. However, vent-community recovery may be much slower where volcanic eruptions occur less frequently. In fact, vent communities on active sulfides in the South Pacific exhibit remarkable stability over a decadal timescale [12], suggesting that recovery from mining disturbance in more stable vent ecosystems could be slower. The massive sulfides of mining interest were formed over thousands of years, so their ecosystem dynamics may be attuned to similarly lengthy timescales. However, the biodiversity and dynamics of entire massive sulfide ecosystems are so poorly understood [6] that recovery times cannot be reliably estimated.

(iii) The deep sea is not a pristine wilderness (e.g., [10,13]).

This assertion implies that conservation of deep-sea ecosystems is not warranted since they are already damaged. It is true that human activities influence the entire planet, with fishing, climate change, and pollution penetrating to the deep sea. However, most hydrothermal vents and abyssal areas almost certainly remain among the most intact ecosystems on the planet, largely buffered from anthropogenic damage by their enormous separation from the focus of human activities in the coastal, upper ocean.

Critical Knowledge Gaps

The development of environmental regulations for seabed mining is hampered by profound gaps in basic knowledge about deep-sea ecosystems and in our ability to predict responses to stressors, although resilience to mining disturbance is generally expected to be low [14]. We do know that some deep-sea animals (e.g., corals on seamounts) can live for centuries but for most we lack basic biological data. Growth rates, life histories, and tolerance to stressors (both acute and chronic) for targeted fauna are needed to fully define the spatial and temporal scales of impacts and potentials for recovery from mining. We have very limited knowledge of the larval connectivity required to maintain communities under both natural and mining-stressed conditions. Furthermore, the combined potential impacts from mining (e.g., habitat removal/burial, sediment plumes) and climate change inflate uncertainties and may exacerbate disturbance from mining.

Despite significant funding by governments and industry for deep-sea research, basic documentation of biodiversity and natural variability in areas targeted for deep-seabed mining is incomplete. Recent discoveries underscore the remarkable, unknown species richness and complexity of these communities. While many terrestrial environmental impact assessments work with extensive faunal lists and well-characterized ecosystem functions and services, deep-sea biologists are very early in the process of documenting species occurrences, community structure, biogeography, and ecosystem functions in all the targeted habitats. For example, communities of inactive massive sulfides are mostly undescribed [6]; the vast majority of seamounts in the ocean have never been sampled [7]; the macrofauna and meiofauna of cobalt-rich crust deposits are practically unknown; and most of the >2000 faunal

Box 1. Potential Scales of Mining Impacts on Nodule-Rich Habitats in the CCZ.

Nodule-rich areas cover ~10–30% of the three ecological subregions with the highest nodule abundances in the central CCZ (Figure 1), yielding ~100 000 to 300 000 km^2 of nodule-rich habitat within each of these subregions [11]. For economic viability, a contractor is expected to mine nodule-rich beds at ~400 km^2 year^{-1} [8], removing nodules and directly disturbing sediments over ~8000 km^2 during a 20-year mining period. Nodule-rich beds typically occur in bands a few kilometers wide separated by intervening nodule-poor (i.e., not mineable) bands 2–10 km wide (Figure I, Figure S1 in the supplemental information online) [2,13]. Modeling of sediment plumes predicts sedimentation rates and suspended-particle concentrations 3–4 orders of magnitude above baseline levels at least 10 km from direct mining (e.g., [16]), with the consequence that surrounding, unmined nodule-poor bands are also expected to be heavily impacted by burial and turbidity. Thus, the disturbance from a single mining operation could easily be 2–4-fold larger than its direct mining footprint (see the supplemental information online), affecting up to ~32 000 km^2 over 20 years. Since several subregions contain four to eight exploration contracts (Figure 1A), mining in the 16 contract areas could remove/bury/smother a substantial proportion of the nodule habitat within subregions and across the entire CCZ (>500 000 km^2).

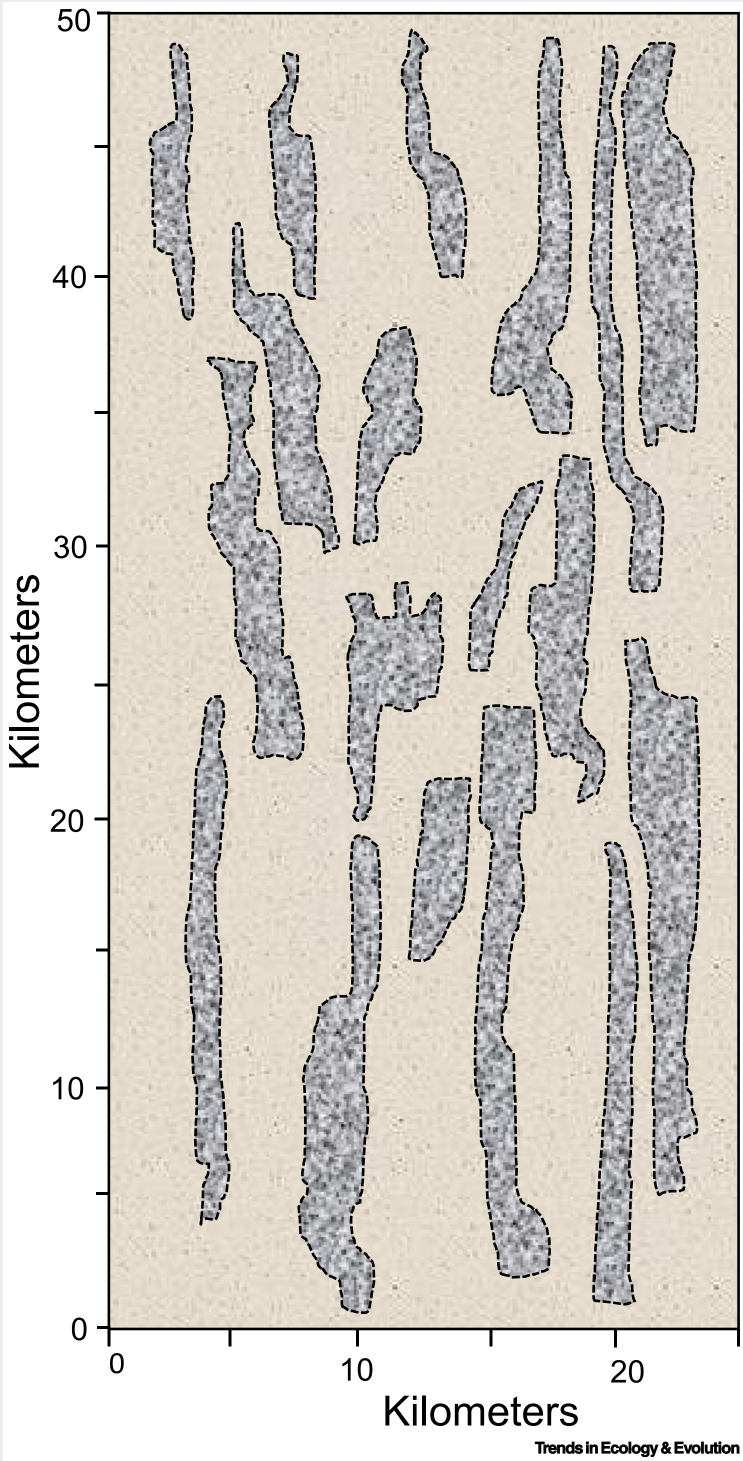

Figure I. Size and Position of Potential Nodule Mining Blocks (Grey Mottling) in a Part of the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) Exploration Contract Area in the Clarion Clipperton Zone (CCZ). Approximately 25% of the total area is considered viable to mine for polymetallic nodules. Data from Thiel *et al.* [13].

species recently collected in the eastern CCZ are new to science (e.g., [2]).

The behavior of sediment plumes that will be generated directly from seabed mining and from reinjection of mining wastes into the deep sea from surface vessels is also poorly understood. Particle plumes and dissolved chemicals will impact areas larger than the mine site – but how much larger? In the CCZ, with the clearest bottom waters and among the lowest sedimentation rates in the ocean [15], sensitivities to enhanced turbidity and sedimentation are expected to be high, especially when exposure times may last for months to years. Sensitivity thresholds to guide monitoring efforts are very poorly delimited since available data come from shallow-water ecosystems where background levels of sedimentation and turbidity are orders of magnitude higher. Furthermore, we remain unable to predict effects on pelagic ecosystems in response to plumes, noise, and spills because mining technologies are still in development, and the deep pelagic ecosystems are extremely poorly studied.

The Road to Exploitation

The ISA plans to complete exploitation regulations to enable active seabed mining by 2021. A major obstacle is the uncertainty around the impacts of deep-seabed mining on biodiversity and ecosystem services. Furthermore, seabed-mining impacts are unlikely to be fully understood until full-scale mining has been monitored for years. Thus, the precautionary approach will be a key management tool, for example, allowing only one mining operation to proceed until the environmental impacts of mining this seabed mineral are well documented.

Given the unlikelihood of filling all knowledge gaps within the next few years, an important step for deep-sea scientists and regulators is identifying the information most useful to management decisions. Large scientific uncertainties can lead to disagreements about potential impacts, but this should promote healthy debate and focus research and monitoring priorities. The deep sea contains many of the most pristine, poorly studied, and evolutionarily remarkable ecosystems on our planet – *in situ* scientific knowledge addressing the full scales and intensities of seabed mining should be obtained and properly applied to sustain biodiversity and ecosystem functions in the deep sea if mining is to proceed.

Author Contributions

All authors contributed to the content and writing.

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Supplemental Information

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